



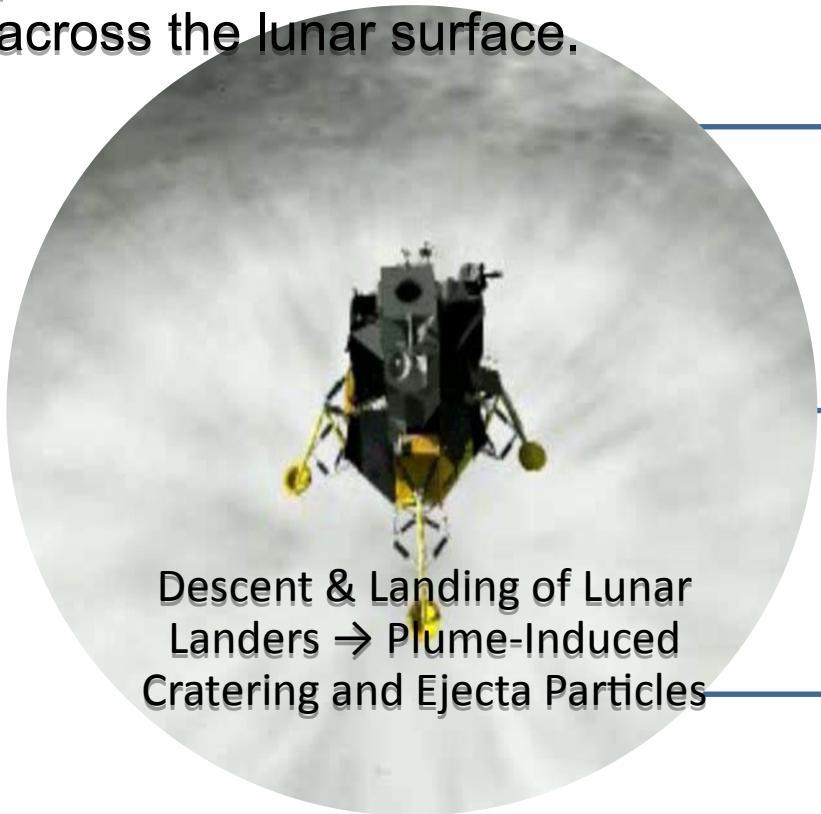
Plume Surface Interaction: Surface Excavation and Construction Impacts

Michelle M. Munk | EDL System Capability Lead | 08.20.21

Lunar Lander Plumes are a Significant Source of Dust



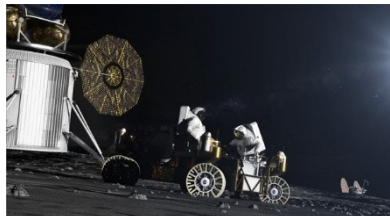
Challenge: **Lunar dust** is a significant obstacle to achieving a sustainable human presence on the Moon, and **lunar landers** will be a **major source of dust transport** across the lunar surface.



Descent & Landing of Lunar Landers → Plume-Induced Cratering and Ejecta Particles



Impact Hazards for Orion, HLS LE/AE, and Gateway



Dust Mitigation Strategies

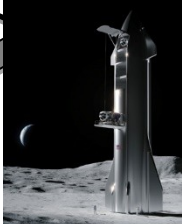
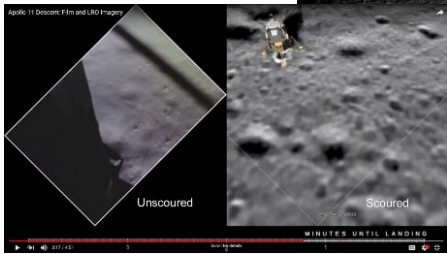
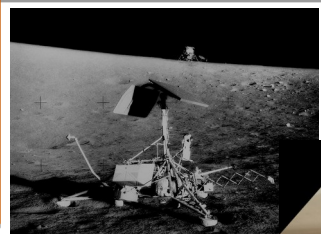


Chart Credit: Jim Mantovani, KSC

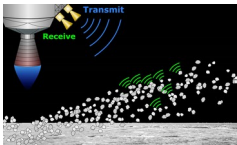


Lunar Surface Ops (Inspection & Removal)

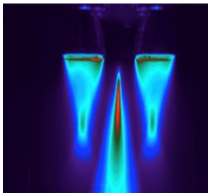


Previous studies of PSI effects relied on data from Apollo 12/Surveyor 3, analog Apollo video/images, and indirect evidence of damage (Curiosity)

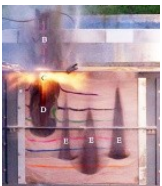
Understand



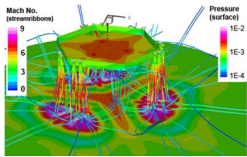
Ejecta



Plume



Erosion



Lander Environment

Plume Surface Interaction Project Overview



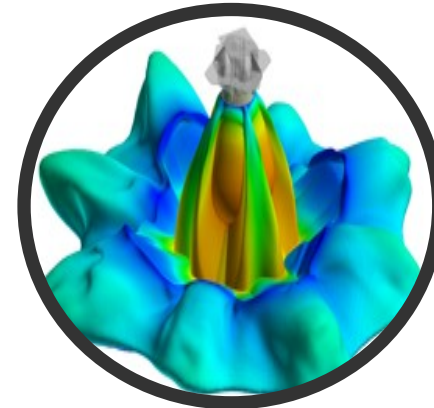
OBJECTIVE: Provide tools and data to better predict environments created by the impingement of descent thruster rocket plumes on planetary bodies, enabling improved design and risk analysis of landing vehicles and surface assets.

Partners:

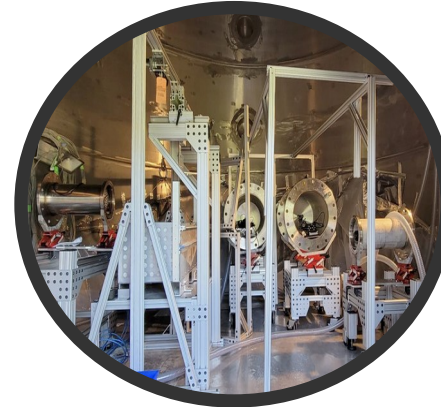
- MSFC (Lead)
- LaRC
- KSC
- GRC
- JPL
- Johns Hopkins University, University of Michigan, University of Central Florida, University of California – Davis, Mississippi State University, Stevens Institute of Technology

Customers:

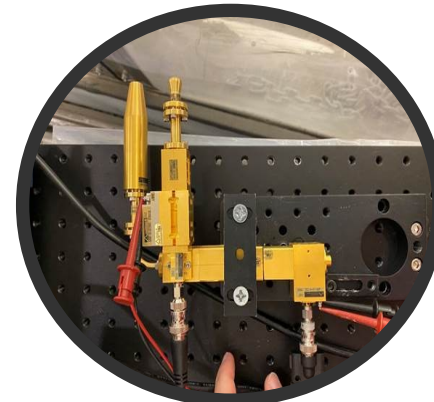
- Space Technology (Game Changing Development Program)
- Science (CLPS, Mars, other bodies)
- Human Exploration and Operations (Human Landing System, Human Mars)
- Commercial entities
- International partners/coordination bodies



1
Predictive Simulation
Capability



2
Ground Tests



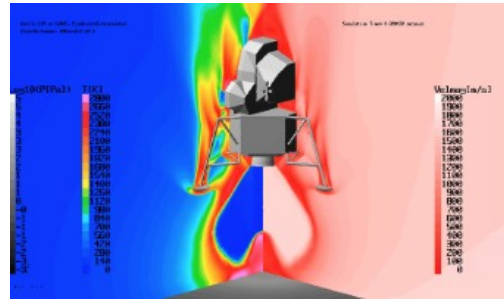
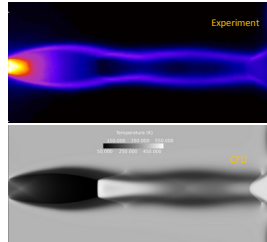
3
Flight
Instrumentation

Predictive Simulation Capability Approach



Task 1: Plume Flow in Low-Pressure Environment

- Lunar vacuum and Mars low pressure environments require mixed continuum-rarefied flow simulation capabilities.
- Production CFD code has mixed continuum-rarefied (NS/Boltzmann) flow solver capability implemented; however, it has not yet been validated.
- JPL Research code is implementing a rarefied (DSMC) solver.
- Plume simulations are progressively validated against existing data and PSI ground test data.



Task 3: Regolith Particle Phase Modeling

- Regolith particle phase modeling requires resolving complexities particular to extraterrestrial regolith surface material composition.
- Erosion process and crater shape for Lunar regolith demonstrated to be strongly driven by two factors: irregular particle shapes and poly-disperse particle size mixture.
- Particle phase models will be implemented into predictive simulation tools and matured.
- Predictive simulation tools will be validated against data from PSC Task 2 and new ground test data.

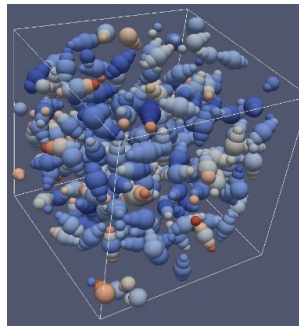
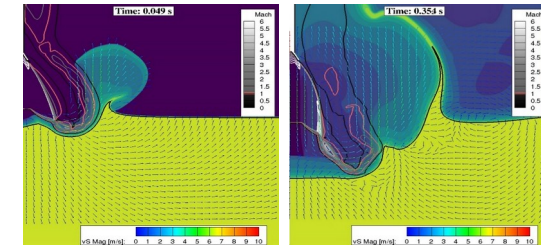
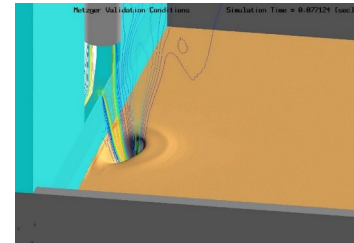


Chart Credit: ER42 Team, MSFC

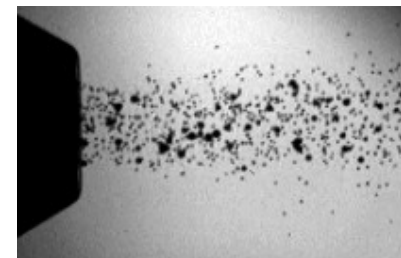
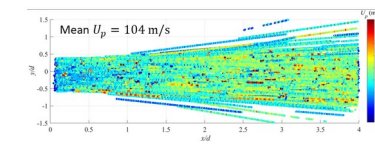
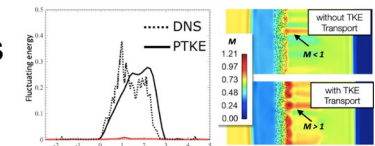
Task 2: Effect of Mixed Continuum/Rarefied Flow on Crater Development and Ejecta Sheets

- Strong dependence of plume induced crater size on flow rarefaction effects with first-order effect on ejecta streams and crater size/shape formation for Lunar environment.
- Prediction simulation tool capability is advanced and validated against existing data and new PSI data.
- Delivers a functional and validated mixed continuum/rarefied PSI simulation capability that accurately captures crater formation and ejecta transport.



Task 4: Gas-Particle Interaction Modeling

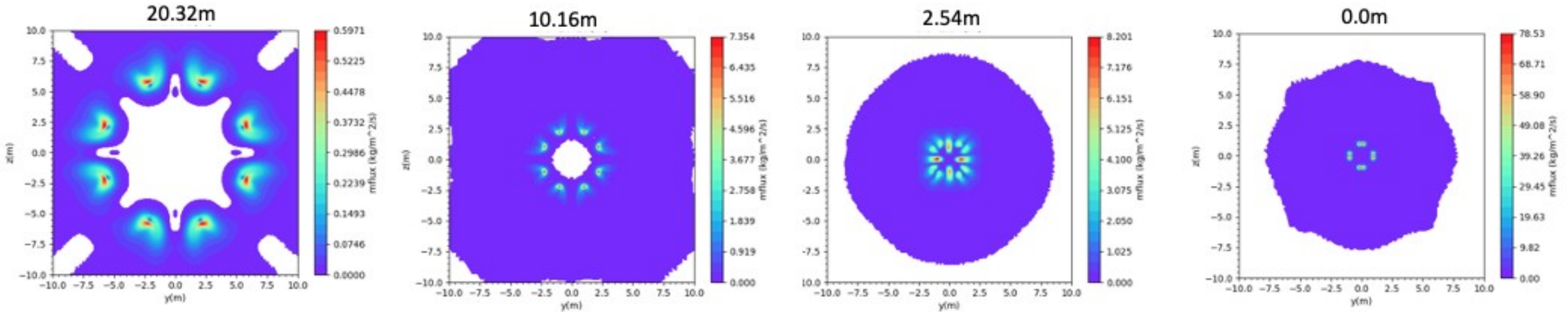
- Large uncertainties exist in gas-particle interactions models implemented in current simulation tools.
- The suitability and accuracy of incompressible modeling formulations on modeling the compressible plume-induced erosion must be addressed; a model for gas-particle cloud kinetics has not been found.
- Accurate gas particle interaction modeling is required for lunar environments and will be implemented through unit physics experiments and development of gas-particle interaction models.



Erosion Predictions for CLPS Instrumentation

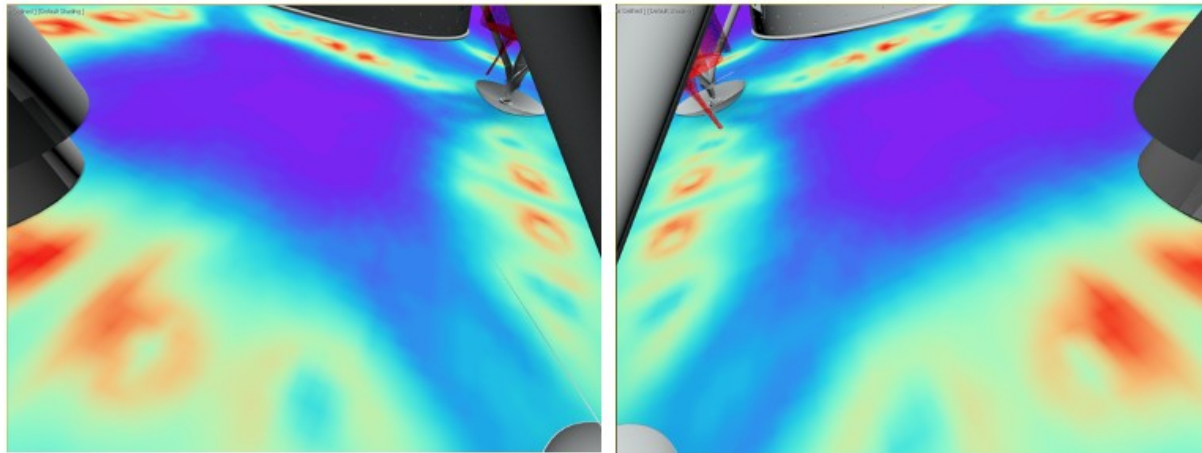


Firefly Blue Ghost Erosion Predictions with Altitude (updated from Lane and Metzger Apollo correlation):



Analysis by ER42, MSFC

SCALPSS Camera FOV
and
expected surface erosion
under Firefly Blue Ghost Lander



Analysis by Olivia Tyrrell, LaRC

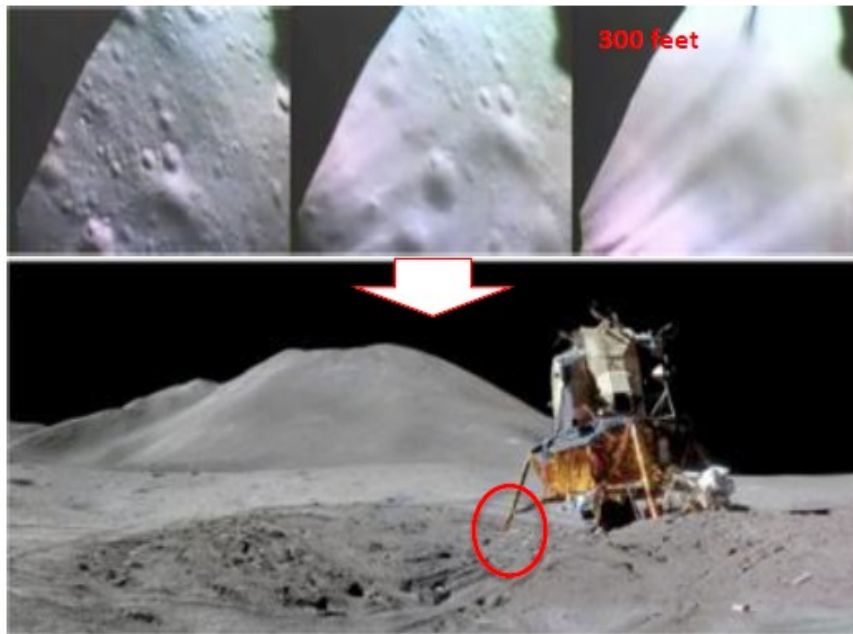
Predictions will (hopefully) be confirmed by flight observations and validated with ground test data!

State of PSI Validation Data



- Inadequate test data and validated modeling \Rightarrow large technical gaps in understanding landing environments
- Computational results are largely qualitative, at present

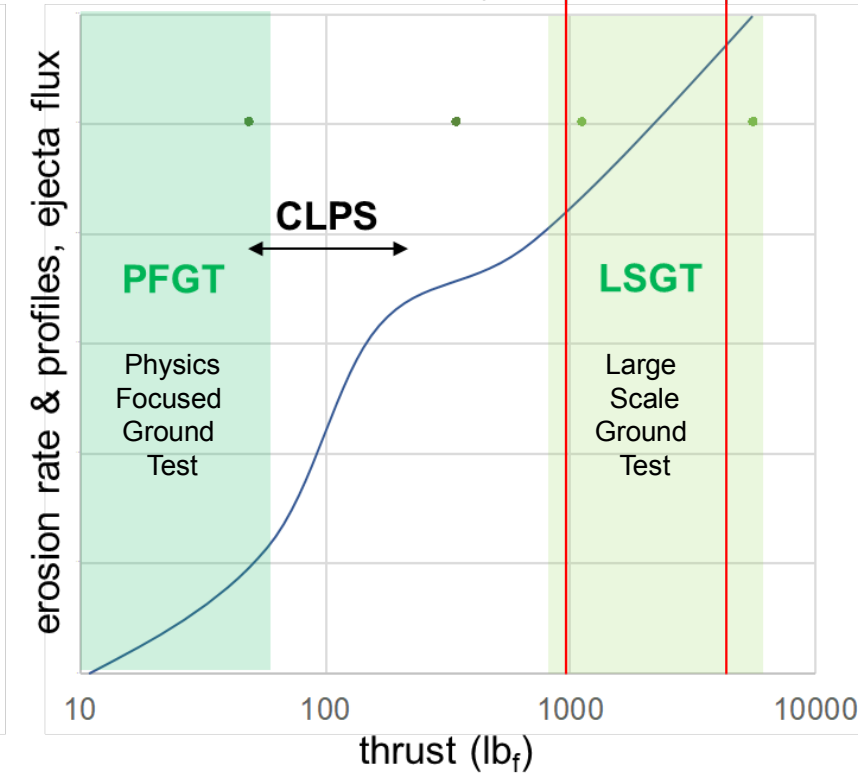
Past Observations



Current Situation



PSI Project HLS



PFGT Objectives



Overall: Measure PSI cratering by collecting data for validating predictive capabilities and to inform future tests at larger scales and more relevant exhaust plume conditions. *Using MSFC Test Stand 300 15' chamber.*

Supersonic Cratering (PFGT1)

- To measure crater formation due to supersonic PSI at ambient atmosphere conditions ranging from Martian to those approaching the Moon.
- Visual data will capture the temporal growth characteristics of crater formation and the behavior of ejecta, and sub-surface pressures will be measured within the regolith bed.

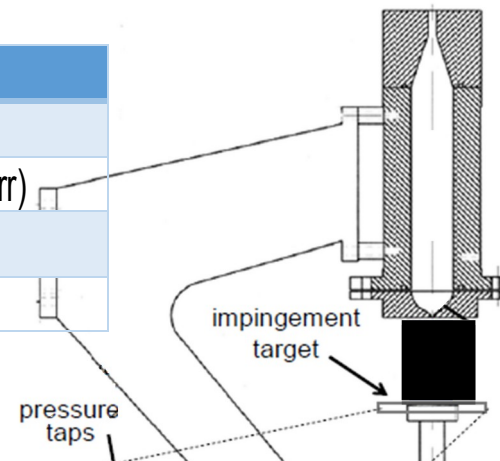
Supersonic Plume Structure/Impingement (PFGT2)

- To visualize supersonic plume structure and to measure impingement pressures at reduced atmospheric conditions in the lunar range.
- Data will be collected using an instrumented impingement plate to quantify gas phase boundary conditions with the same experimental setup used for the cratering and ejecta runs.

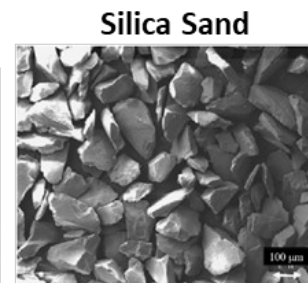
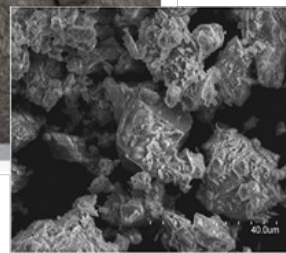
Chart Credit: Chad Eberhart, MSFC

Test Series	Basic Description
Cratering	GN ₂ , split plume, vary quasi-steady flow/vacuum/altitude/regolith, HS/UHS imagery for crater growth and ejecta
Impingement	GN ₂ , split plume, vary quasi-steady flow/vacuum/altitude, surface pressure distribution

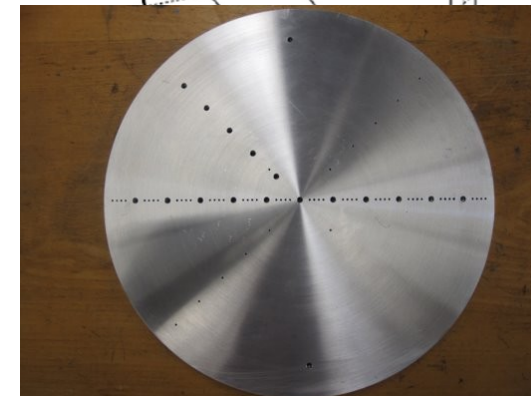
Parameter	Range
h/D_e	3.0 to 10.0
p_{vac}	~7 Pa to 600 Pa (0.053 Torr to 4.5 Torr)
\dot{m}_j	0.32 g/s to 8.6 g/s $\pm 10\%$
$T_{0,j}$	500 K (fixed)



[Suescun-Florez et al., 2018]



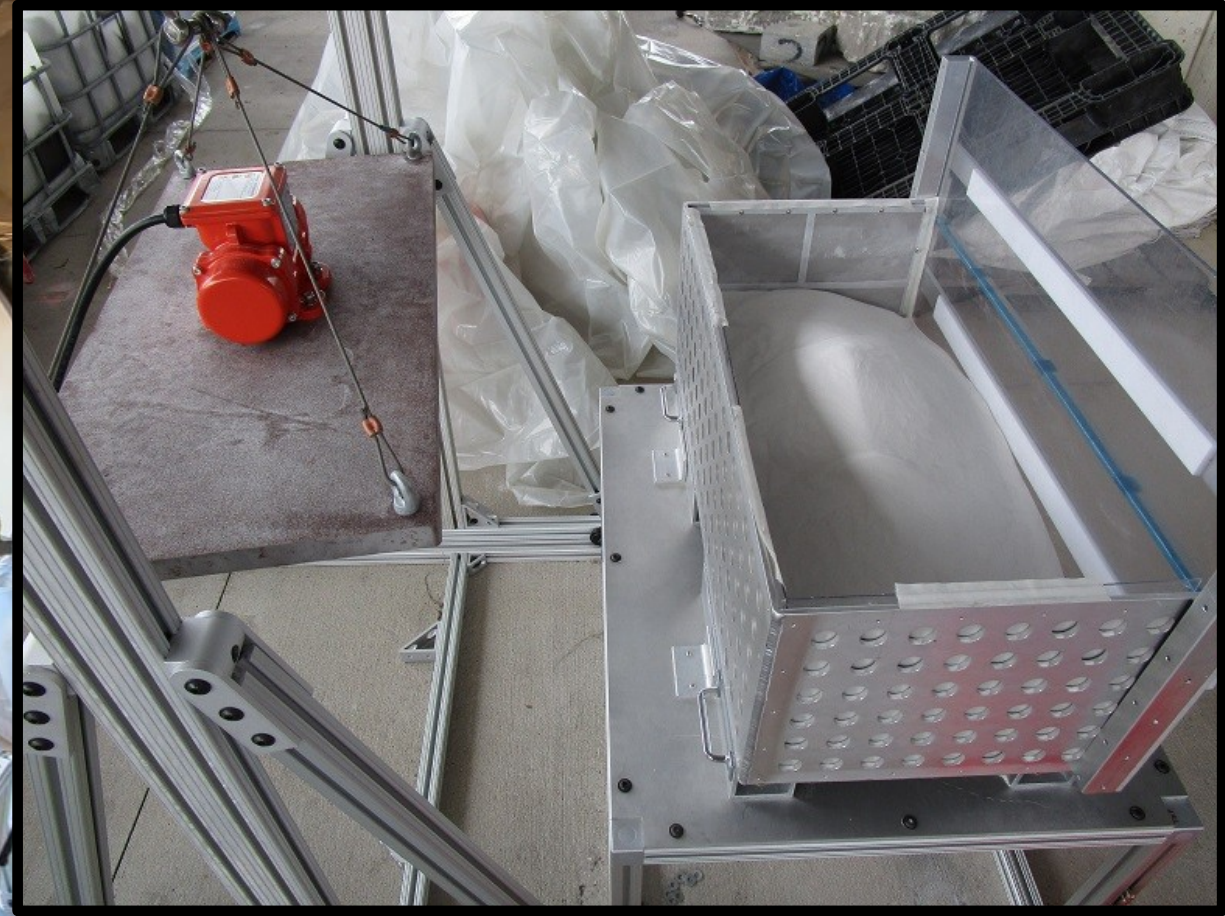
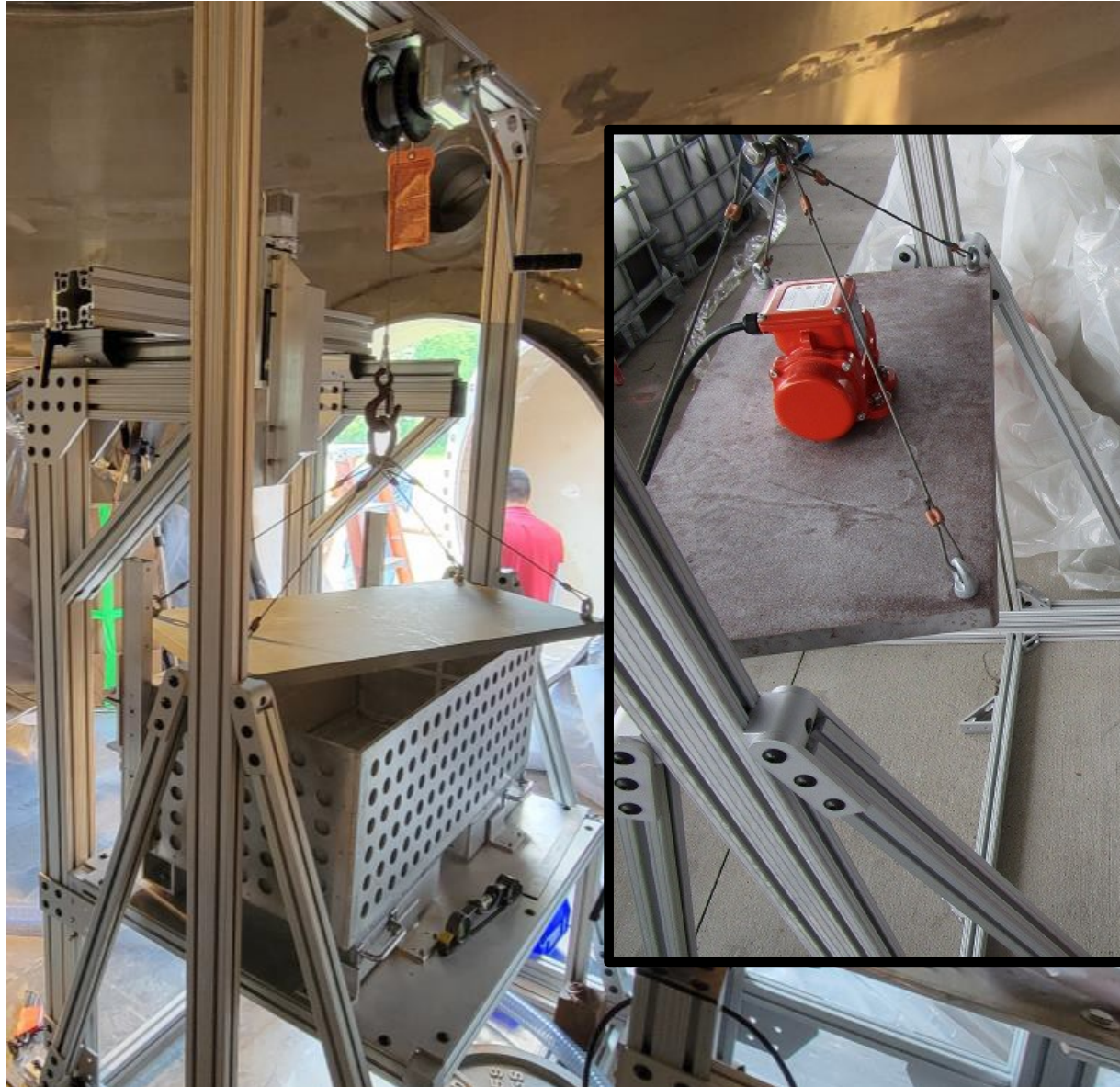
[Arjula et al., 2009.]



PFGT1 Simulants and Soil Bin



Simulant	Characteristics
Mono-disperse Sand	Silica 125-177 μm
Bi-disperse Sand	Silica; 50/50 45-53 μm 125-177 μm
Irregular	BP-1 212-350 μm
Tri-Disperse Mixture	Silica + BP-1
Full-Range Lunar	BP-1
Mono-disperse Spheres	Soda Lime 125-177 μm

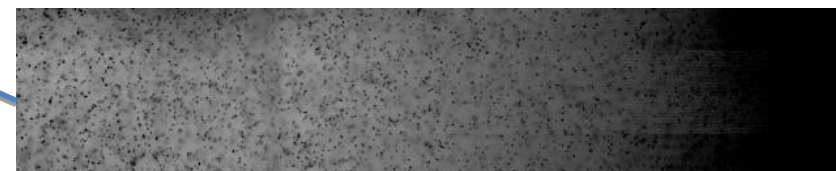
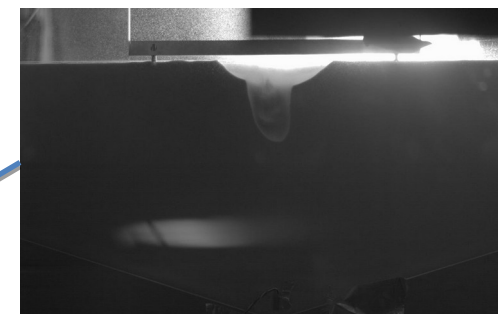
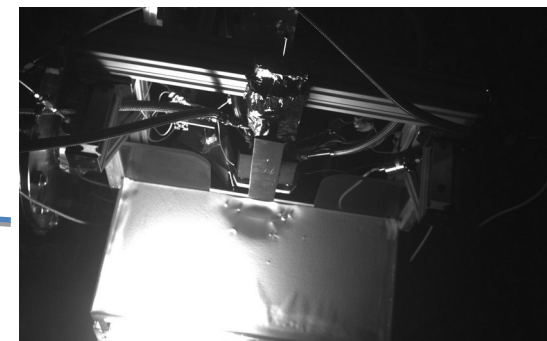
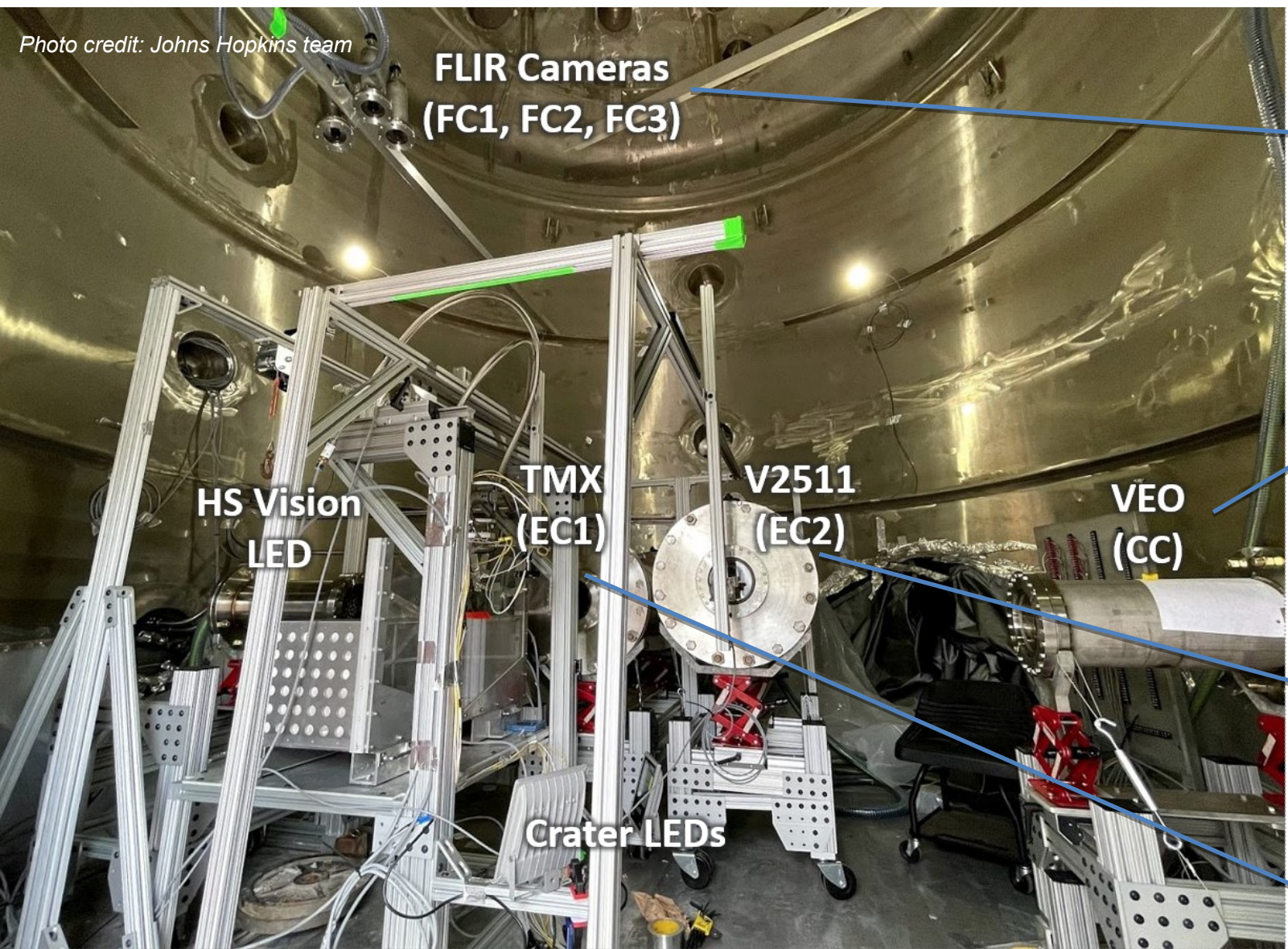


PFGT soil bin setup at KSC (above) and later at MSFC (left).

PFGT1 has Extensive Diagnostics



Photo credit: Johns Hopkins team

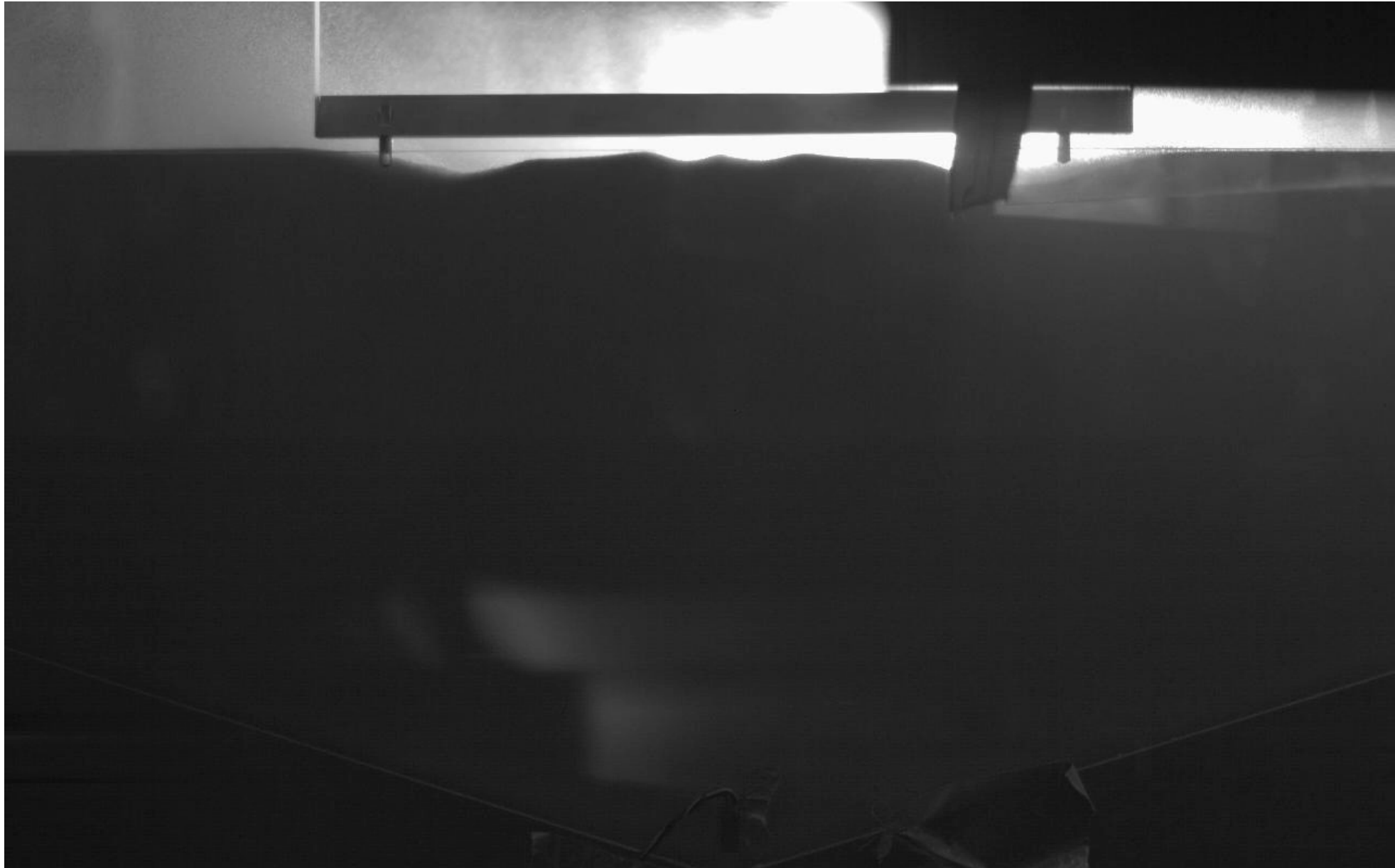


“Deep” Crater Formation in Sand

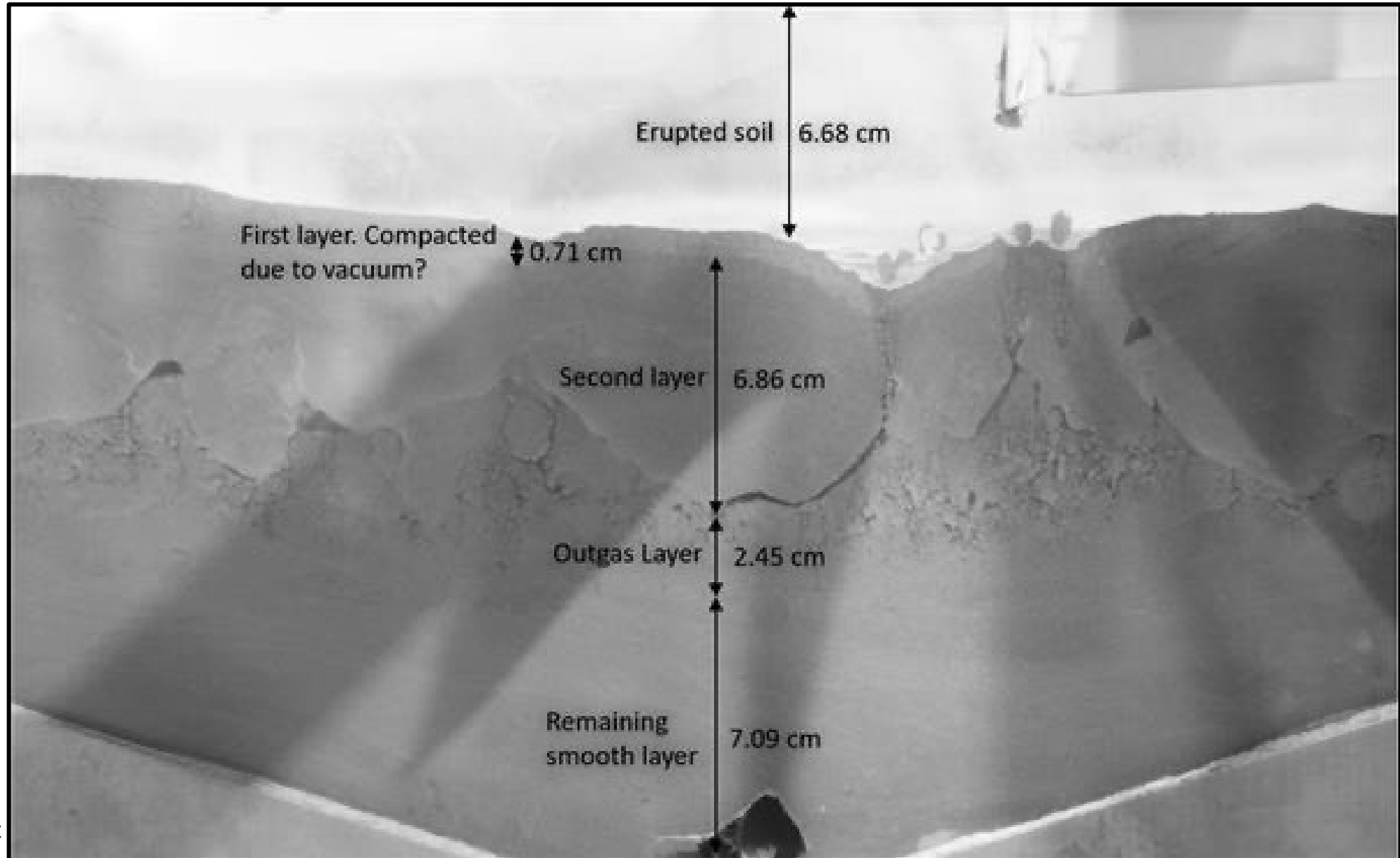


July 28 Test

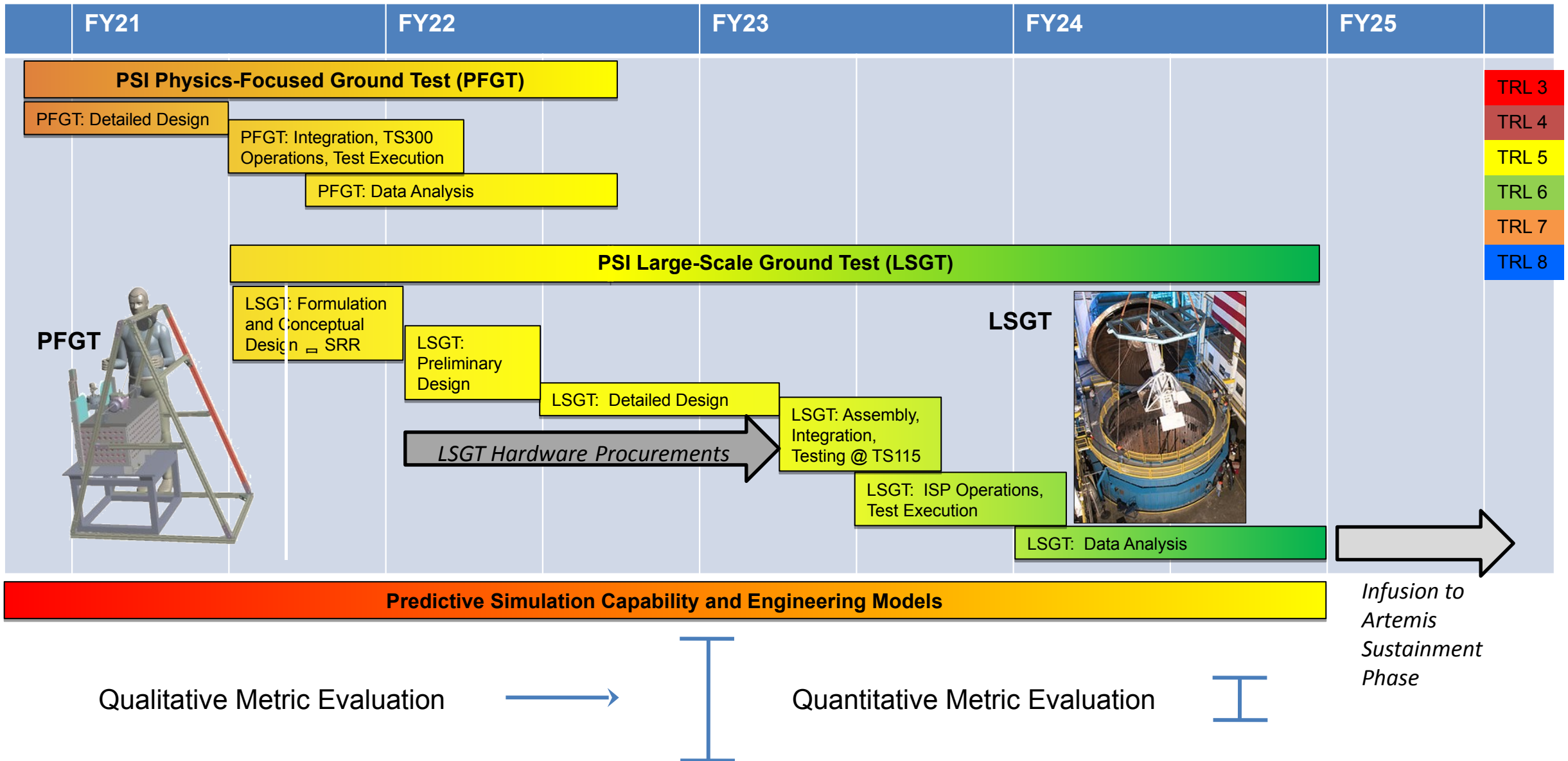
“Annular” Crater Formation in Sand



Next-Level Analysis of Soil Mechanics



PSI Project – Overall Schedule



Summary



Testing efforts will soon provide validation data for predicting plume and ejecta environments, providing inputs to Surface Excavation and Construction activities

- The PSI efforts within STMD are using a 3-pronged approach of simulation, ground test, and flight test to validate models and advance the SOA in understanding landing and ascent induced environments
- The ongoing Physics-Focused Ground Test (PFGT) will develop a high-fidelity parametric database of cratering behaviors in various regolith simulants (simple -> complex), followed by plume impingement plate tests
- Learning valuable lessons about vacuum testing and regolith simulant use
- Upcoming Milestones:
 - PFGT Cratering/Ejecta Testing: through mid-September
 - LSGT Propulsion System SRR: September
 - PFGT Impingement Plate Testing: October/November
 - SCALPSS on CLPS Intuitive Machines lander: March 2022
- Forward work:
 - PFGT Data Processing and Analysis, **Model Updates**
 - SCALPSS 1.1 on CLPS Firefly lander: late 2023
 - Large Scale Ground Test (LSGT) in Q4FY23
 - Instrumentation development for CLPS flight in 2025

